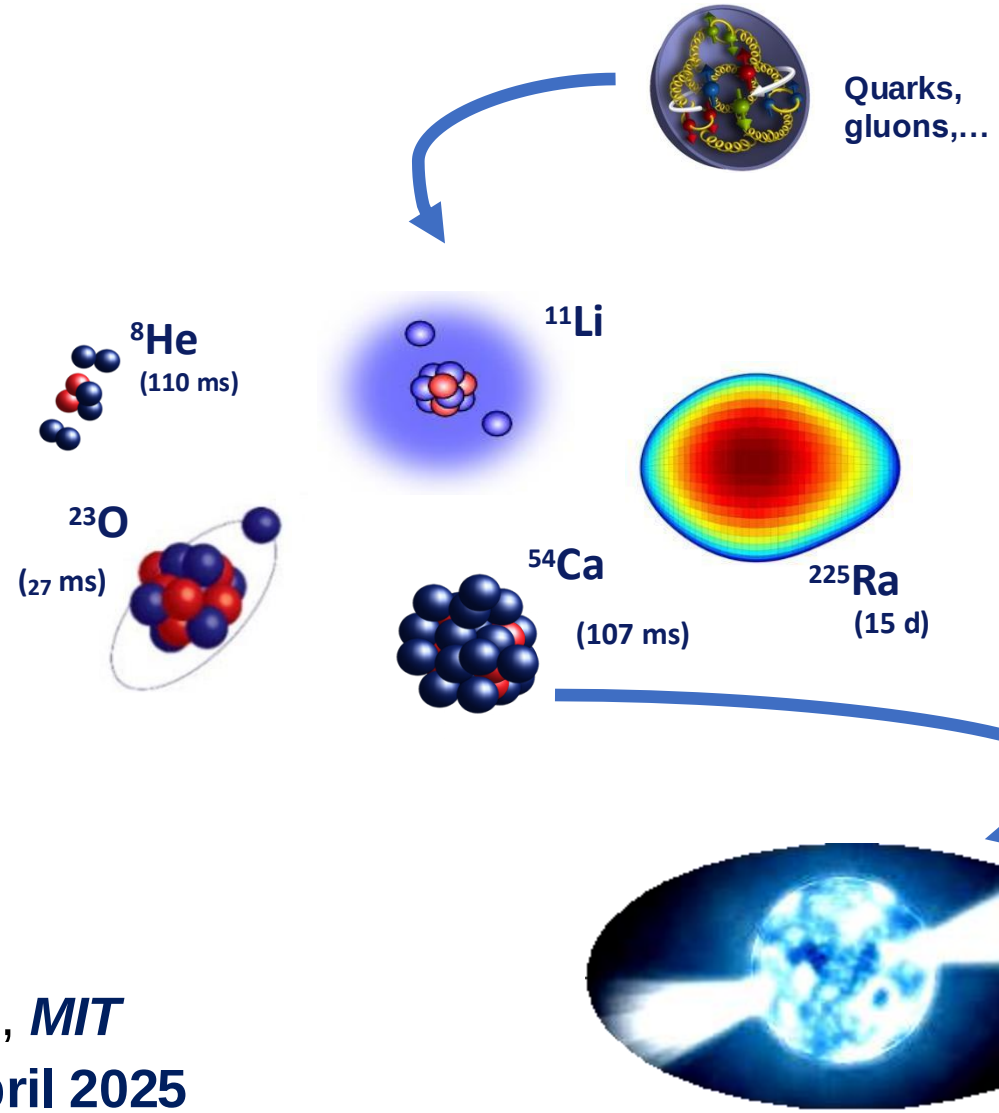
Radioactive Atoms & Molecules are Dying to Reveal New Physics

Figure modified from https://sphereofinfluence360.com/



Ronald F. Garcia Ruiz, *MIT*

NUPAX Open House, April 2025

Radioactive Atoms & Molecules are Dying to Reveal New Physics

Properties of fundamental particles and interactions

- ➔ Why is there more matter than antimatter?
- ➔ Are there new particle and forces?

Properties of nucleons

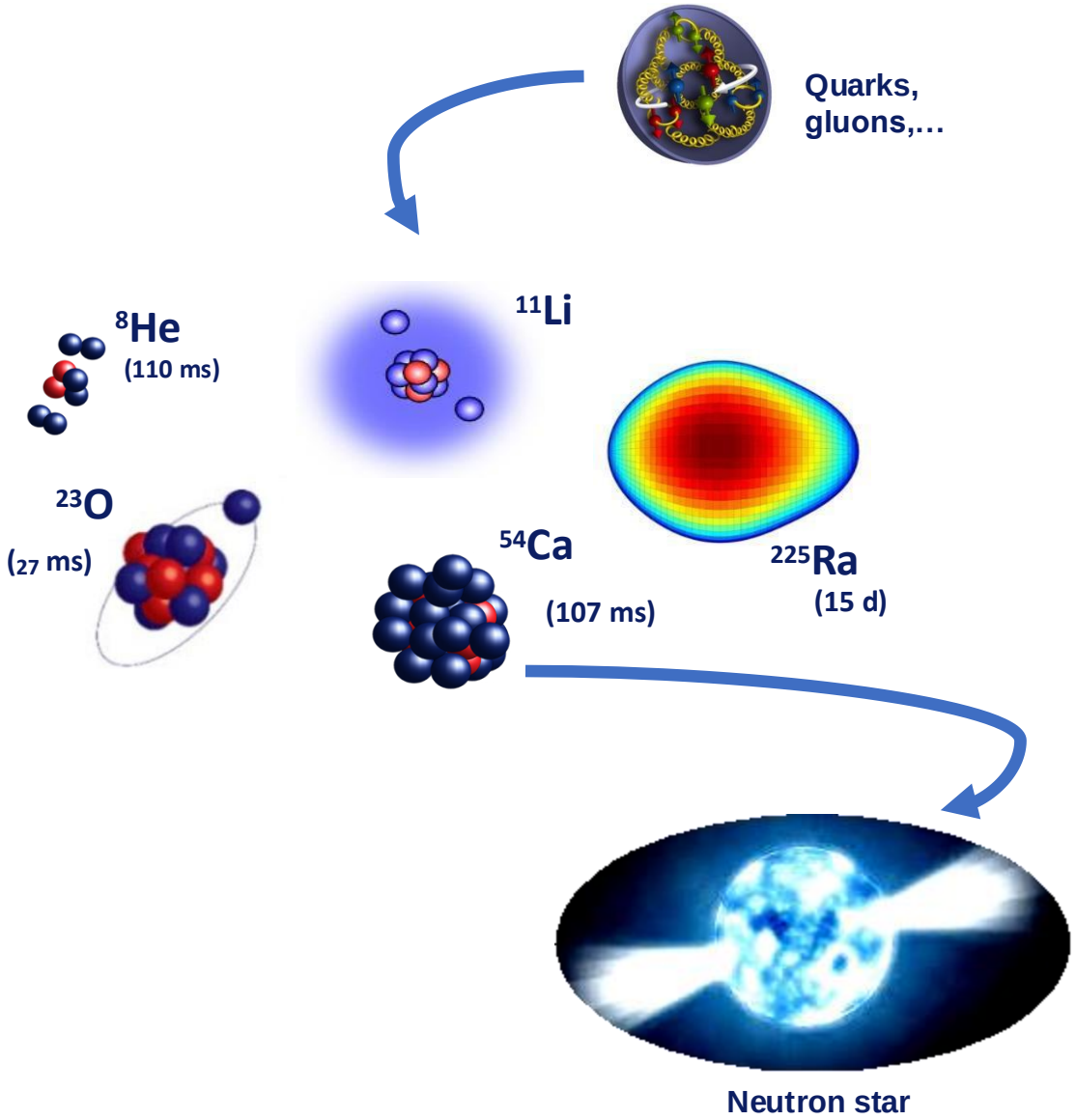
- ➔ How can the nuclear force be explained in terms of fundamental forces?
- ➔ How does dark matter interact with hadrons and leptons?

Properties of nuclei

- ➔ How do nuclear phenomena emerge?
- ➔ Is there a ”Standard Model of the Nucleus”?

Properties of nuclear matter

- ➔ What is the equation of state of nuclear matter?
- ➔ What are the limits of nuclear existence?



Graduate Students

S. Udrescu
(-> U. Chicago)

A. Brinson
NSF Fellowship

H. Kakiota
Ezoe Memorial Fellowship

S. Moroch
Hertz Foundation Fellowship

F. Pastrana
Santo Domingo Fellowship

D. Gonzales
(Harvard)

J. Munoz

M. Fulghieri

F. Shungo

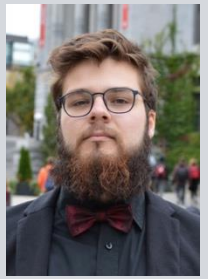
Postdoctoral Researchers

S. Wilkins
Prof. MSU

J. Karthein
Prof. Texas A&M

S. Ebadi
Pappalardo Fellowship

A. Jadbabaie
NSF MPS Ascend Fellow



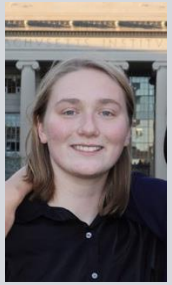
A. Belly
NSERC Fellow

PI

R.F. Garcia Ruiz

Undergraduate Students

N. Ching-Hau



K. Kudela

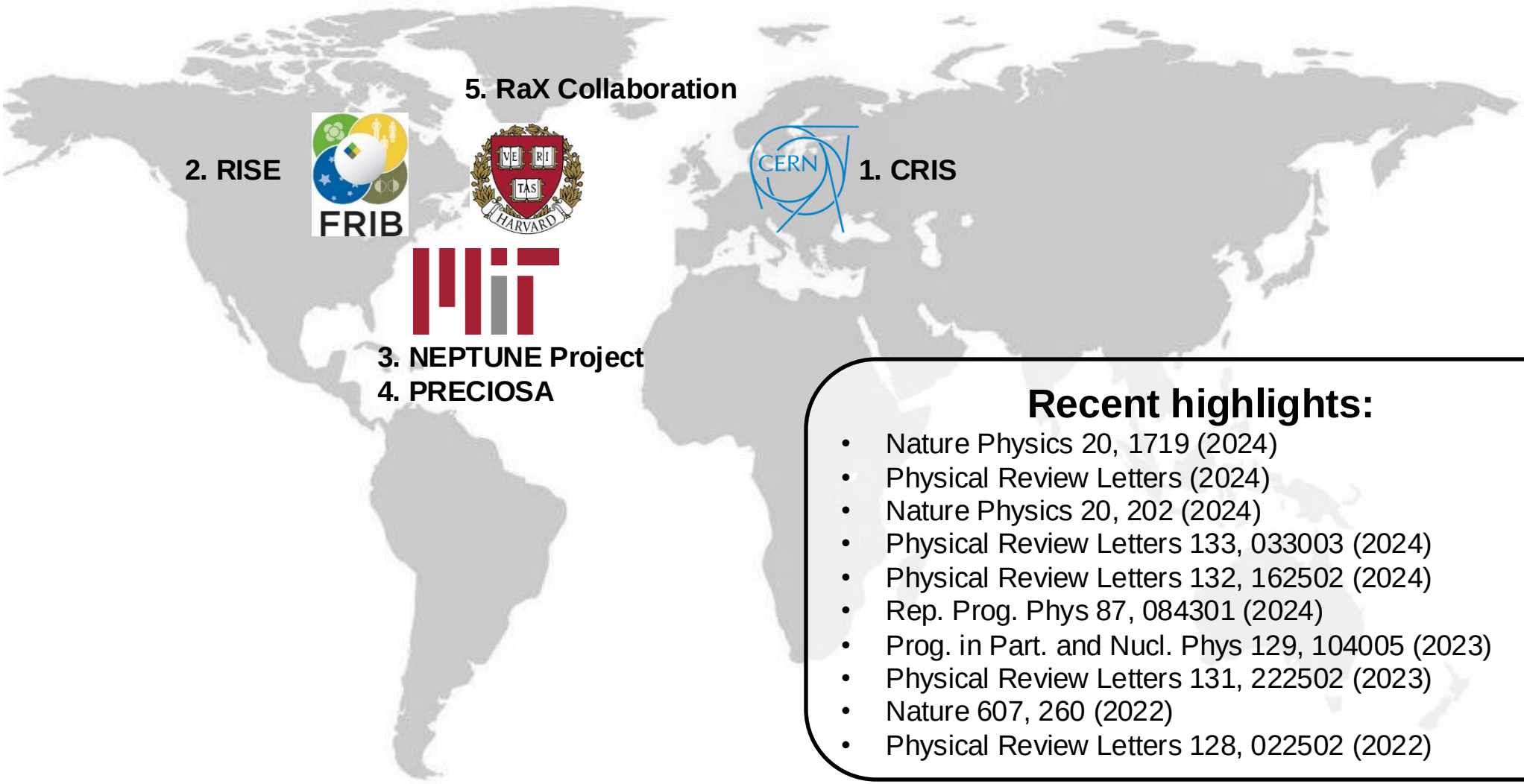
Y. Lewis

R. Hernandez

S. Becerra

FRIB

Bates Lab



5. RaX Collaboration

2. RISE

1. CRIS

3. NEPTUNE Project

4. PRECIOSA

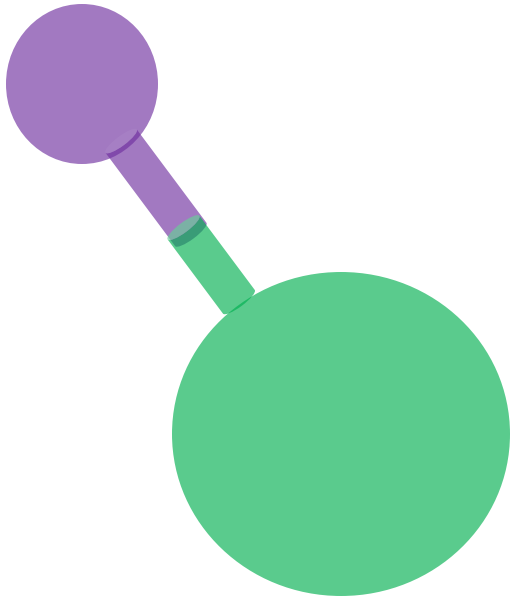
Recent highlights:

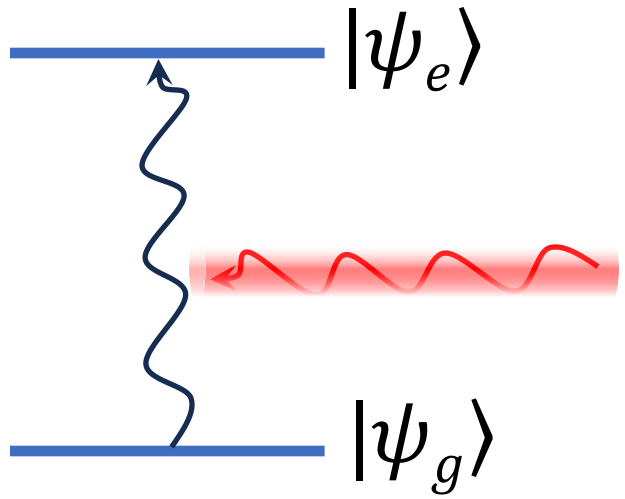
- Nature Physics 20, 1719 (2024)
- Physical Review Letters (2024)
- Nature Physics 20, 202 (2024)
- Physical Review Letters 133, 033003 (2024)
- Physical Review Letters 132, 162502 (2024)
- Rep. Prog. Phys 87, 084301 (2024)
- Prog. in Part. and Nucl. Phys 129, 104005 (2023)
- Physical Review Letters 131, 222502 (2023)
- Nature 607, 260 (2022)
- Physical Review Letters 128, 022502 (2022)

https://www.garciaruizlab.com

Atoms and Molecules for Nuclear Science

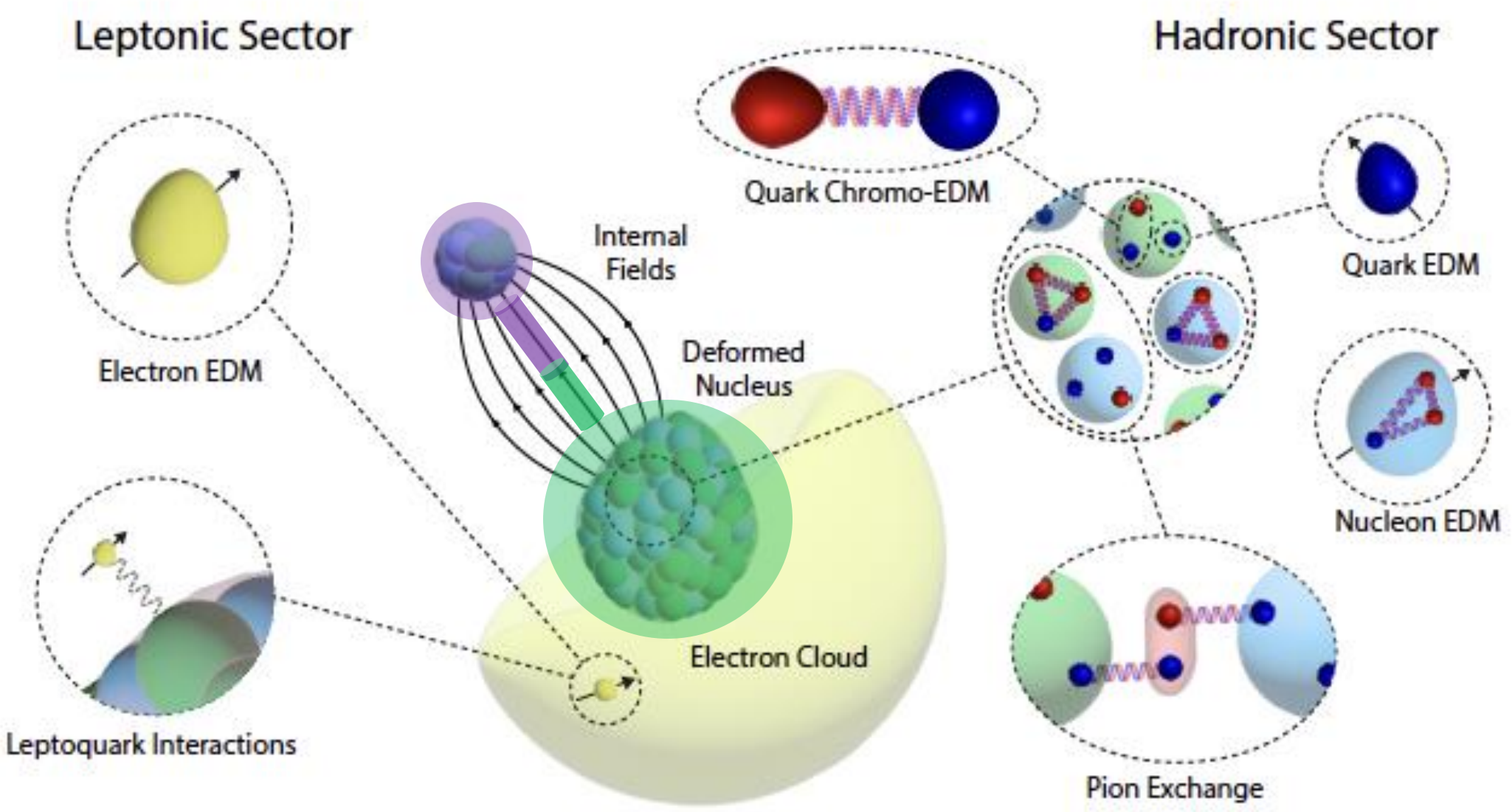
Molecule (AMO view): A two level system





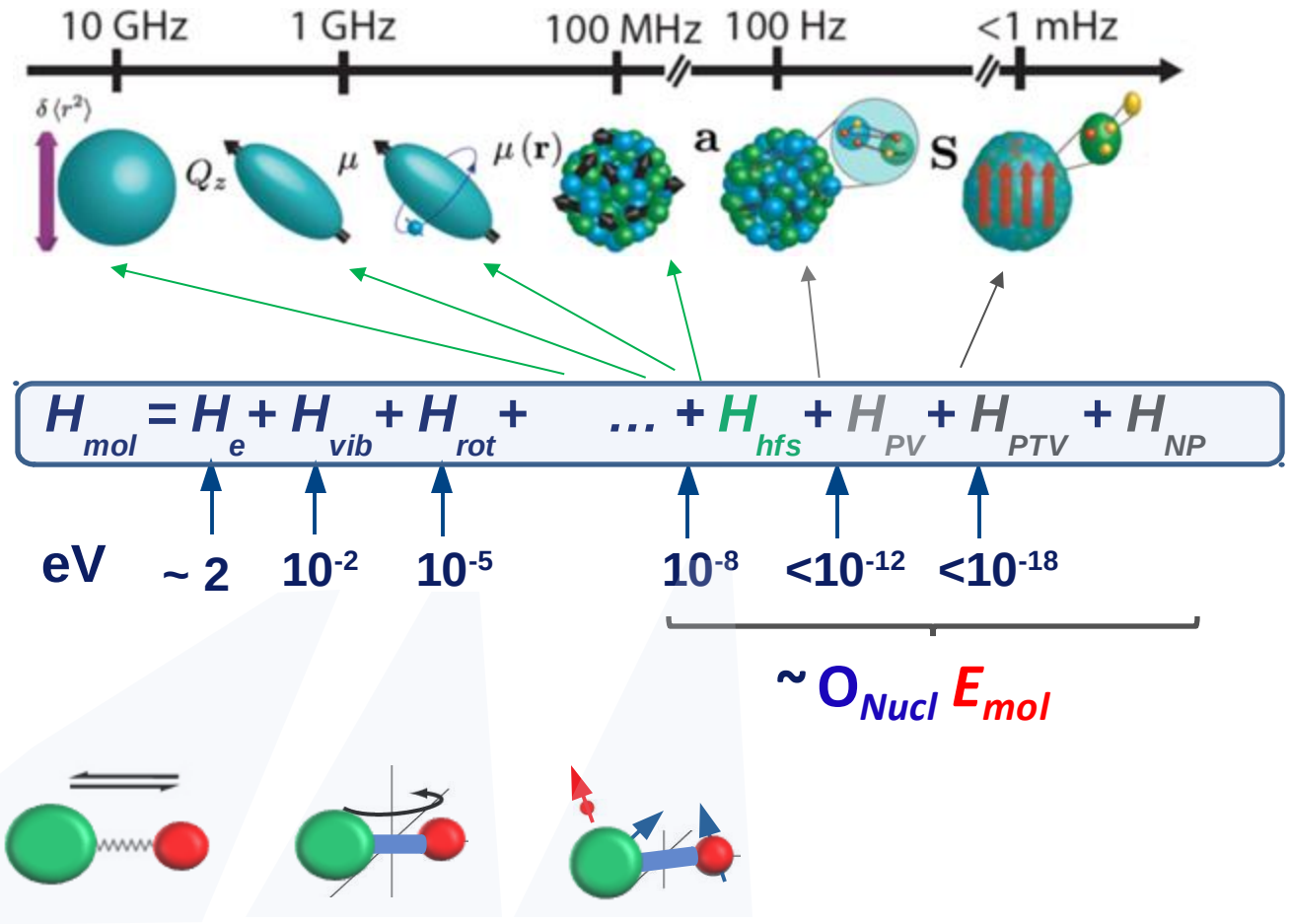
Atoms and Molecules for Nuclear Science

Molecule (NUPAX view): A Laboratory for Nuclear and Particle Physics



Atoms and Molecules for Nuclear Science

Molecules with heavy, exotic nuclei: Ra(Z=88)



[1 eV=241.8 THz]

Recent Results from our group

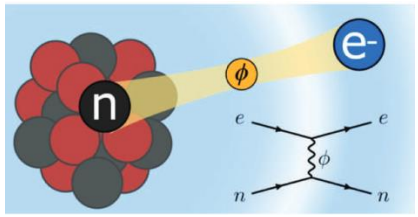
Radioactive Atoms
Radioactive Molecules

Nature Phys 20, 1719 (2024) ✓
Nature 581, 396 (2020) ✓
PRL 127, 033001 (2021) ✓
Nature Phys 20, 202 (2024) ✓
Nature 607, 260 (2022) ✓
Science (2025) ✓

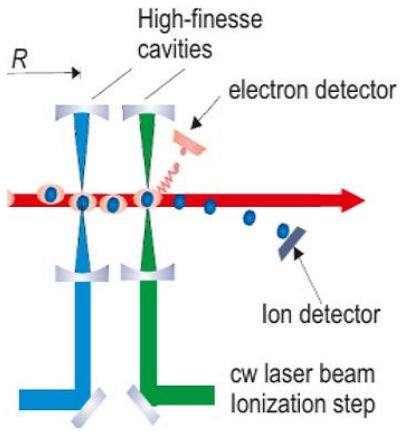
$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{NP}$$

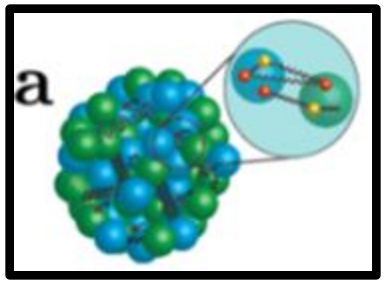
eV ~ 2 10^{-2} 10^{-5} 10^{-8} $<10^{-12}$ $<10^{-18}$

SCORPION

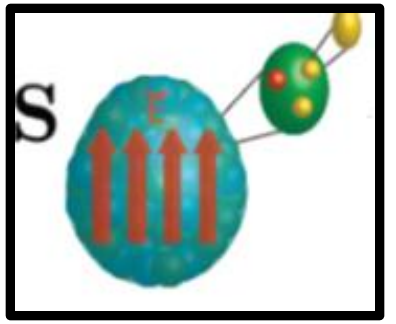


PRECIOSA





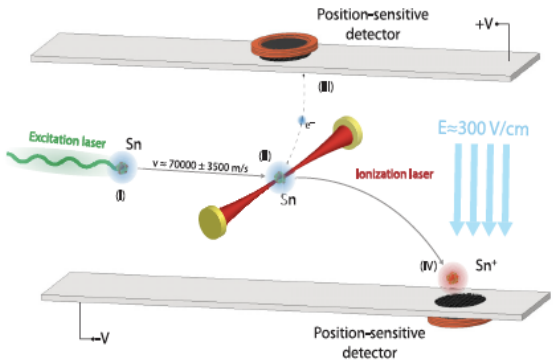
NEPTUNE Project

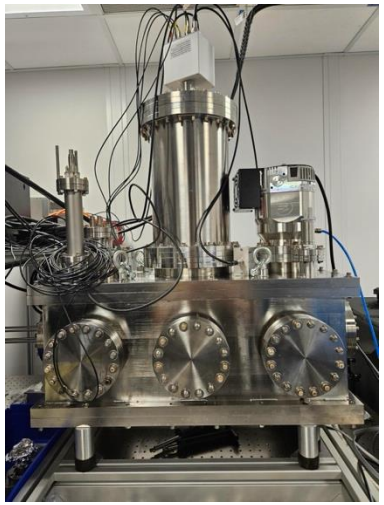


RaX Collaboration

PRECIOSA

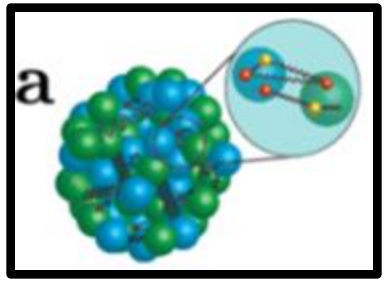
Nuclei and nuclear matter

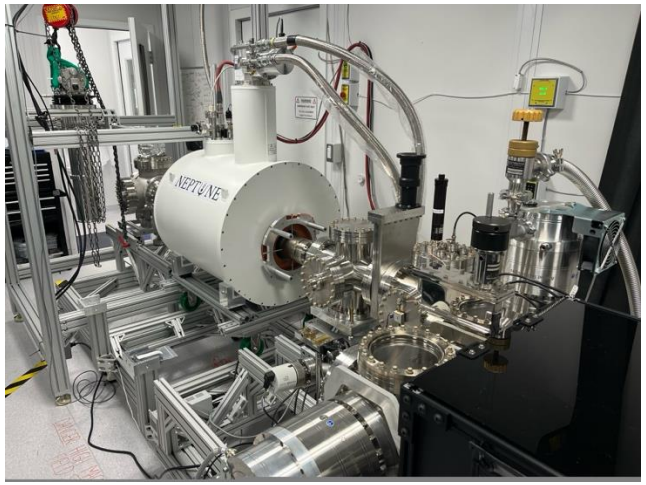




NEPTUNE Project

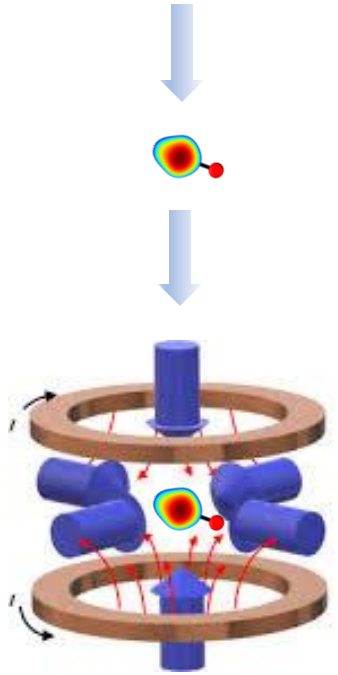
Electroweak properties





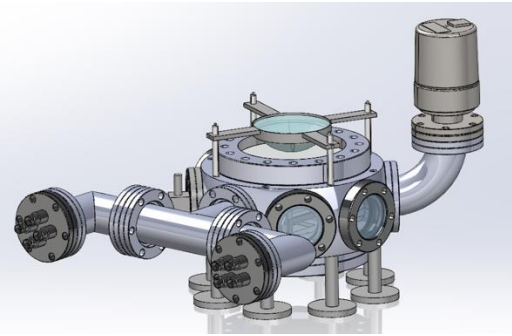
RaX Collaboration

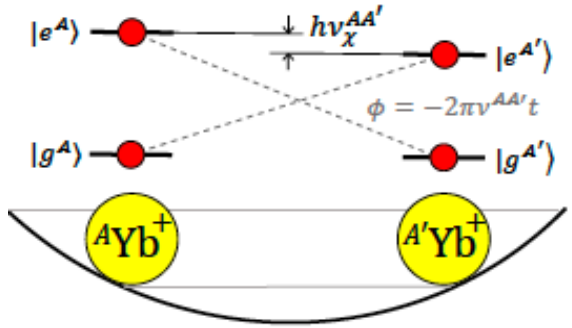
CP-Violation



SCORPION

Dark Matter

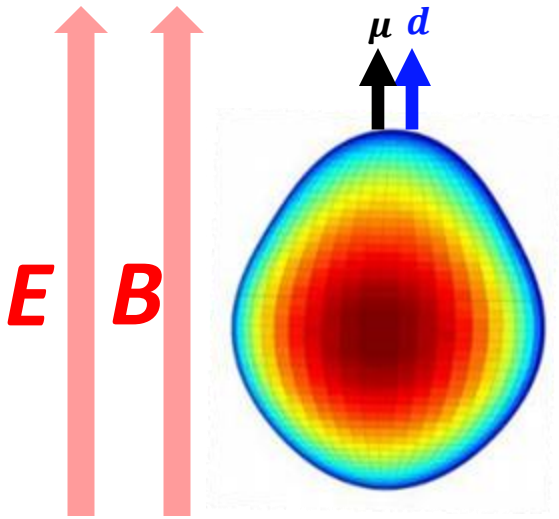




$$|\psi(t)\rangle = |g^i e^j\rangle + \exp\left(-i2\pi\nu_{ij}t\right)|e^i g^j\rangle$$

Electromagnetic properties of a charge distribution

(Produced by the electrons)



Transient fields in reactions:
B ~ 10^3 Tesla
∇E ~ 10^{21} V/cm^2

Atom/molecule

Nuclear

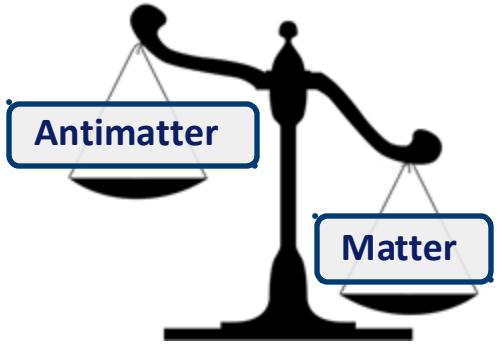
Atom
B ~ 3 Tesla
∇E ~ 10^{18} V/cm^2

Violate Parity and Time reversal

$$H_{sym} = \ldots + c^{1}_{(I,J)}\, \mu.B + c^{1'}_{(I,J)}\, d.E_{eff} + c^{2}_{(I,J)}\, Q.\nabla E + c^{2'}_{(I,J)}\, Q_m.\, \nabla B + \ldots$$

Major Open Questions in Physics and Cosmology

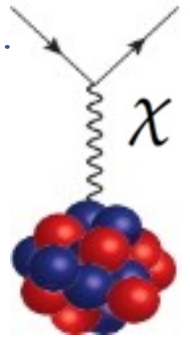
Why is there more matter?



Strong CP problem

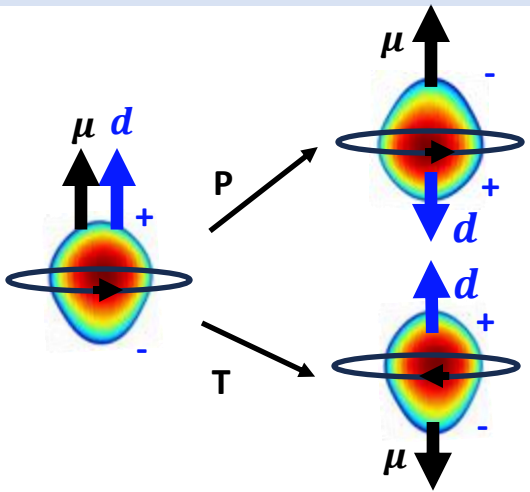
$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$

Are there new particles?



New sources of Time-reversal (CP) violation in nuclei can provide answers to these problems

Electric Dipole Moment (d) ⇄ **Time-reversal violation**



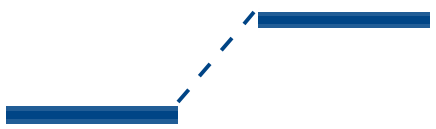
<u>Fundamental Symmetries</u>

Parity (P): $r \rightarrow -r$

Time (T): $t \rightarrow -t$

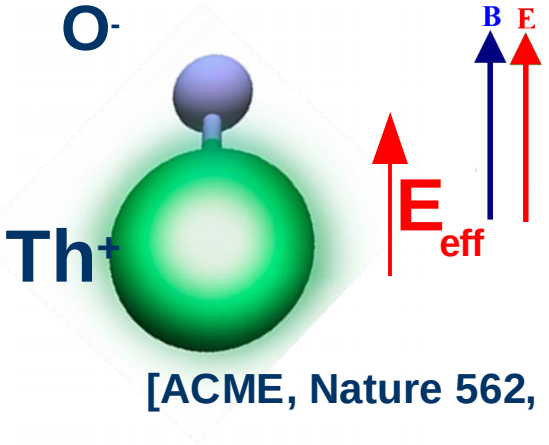
Charge (C): $c \rightarrow \bar{c}$

Molecules for studies of P, T violation



$\sim d_e E_{eff}$

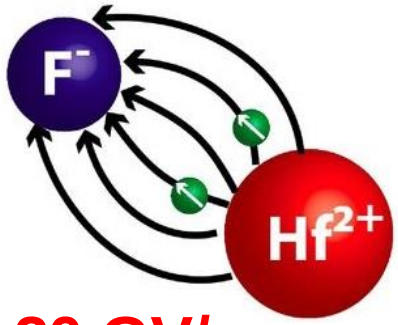
(< 10 μHz)



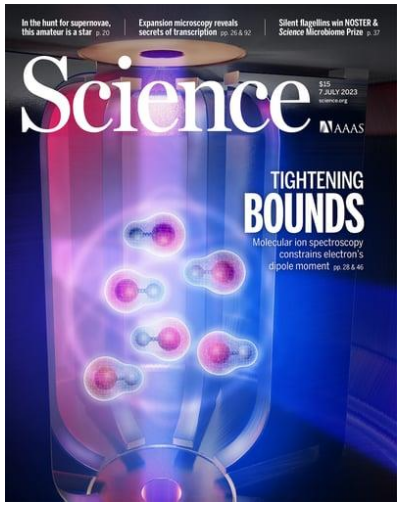
E_{ext} ~1-10 V/cm

E_{eff}~80 GV/cm

[ACME, Nature 562, 355 (2018)]

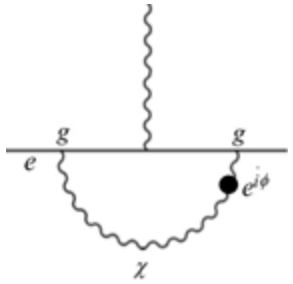


E_{eff}~20 GV/cm



$|d_e| \leq 4.1 \times 10^{-30}$ e · cm

[Roussy et al. Science 381, 46 (2023)]



$$d_e \sim \mu_B \left(\frac{g^2}{2\pi}\right)^N \left(\frac{m_e}{m_\chi}\right)^2 \sin\phi$$

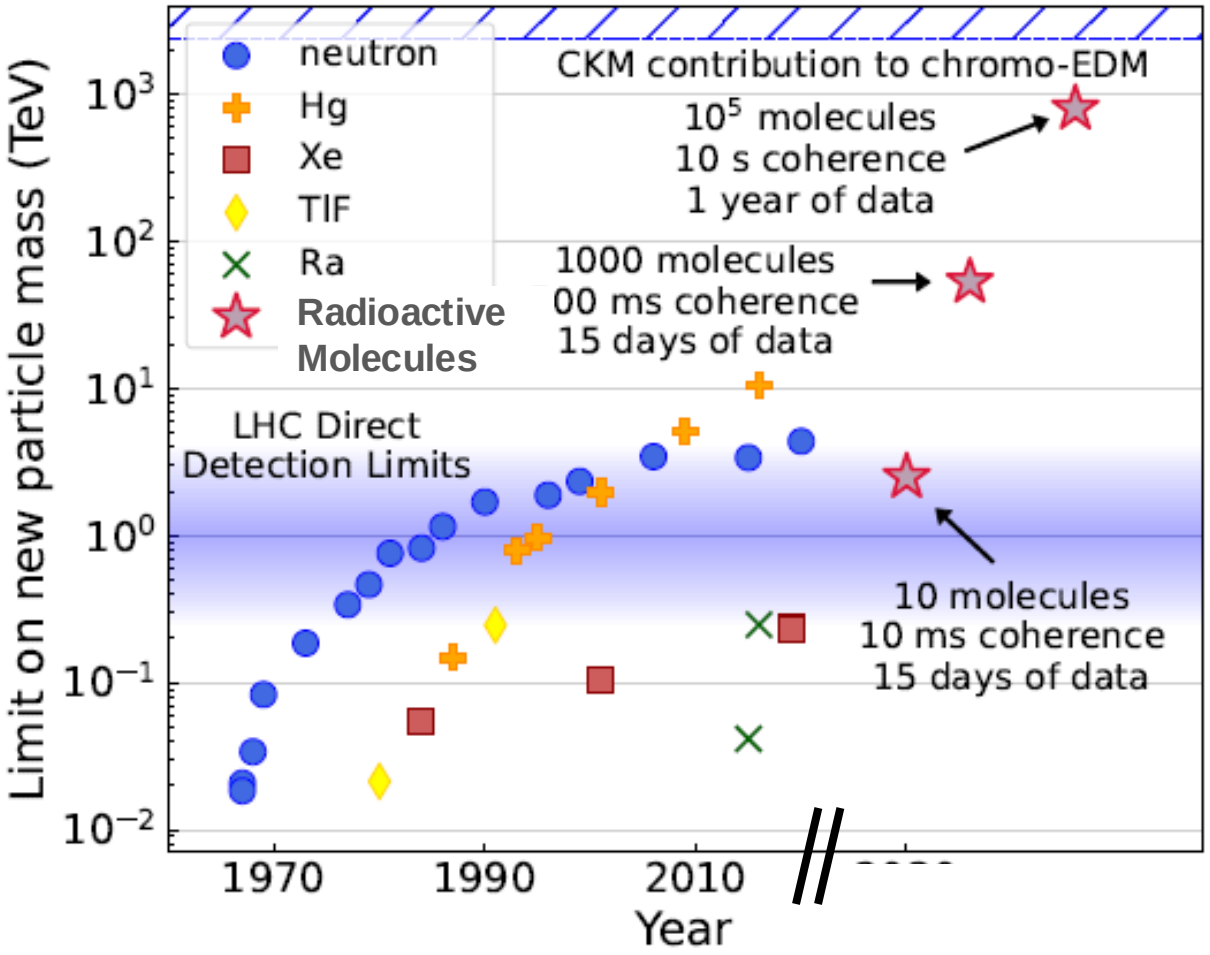
Probing physics @ TeV scale!

[Baron et al. Science 343, 269 (2014)]
[Sandars Phys. Rev. Lett. 18, 1396 (1967)]

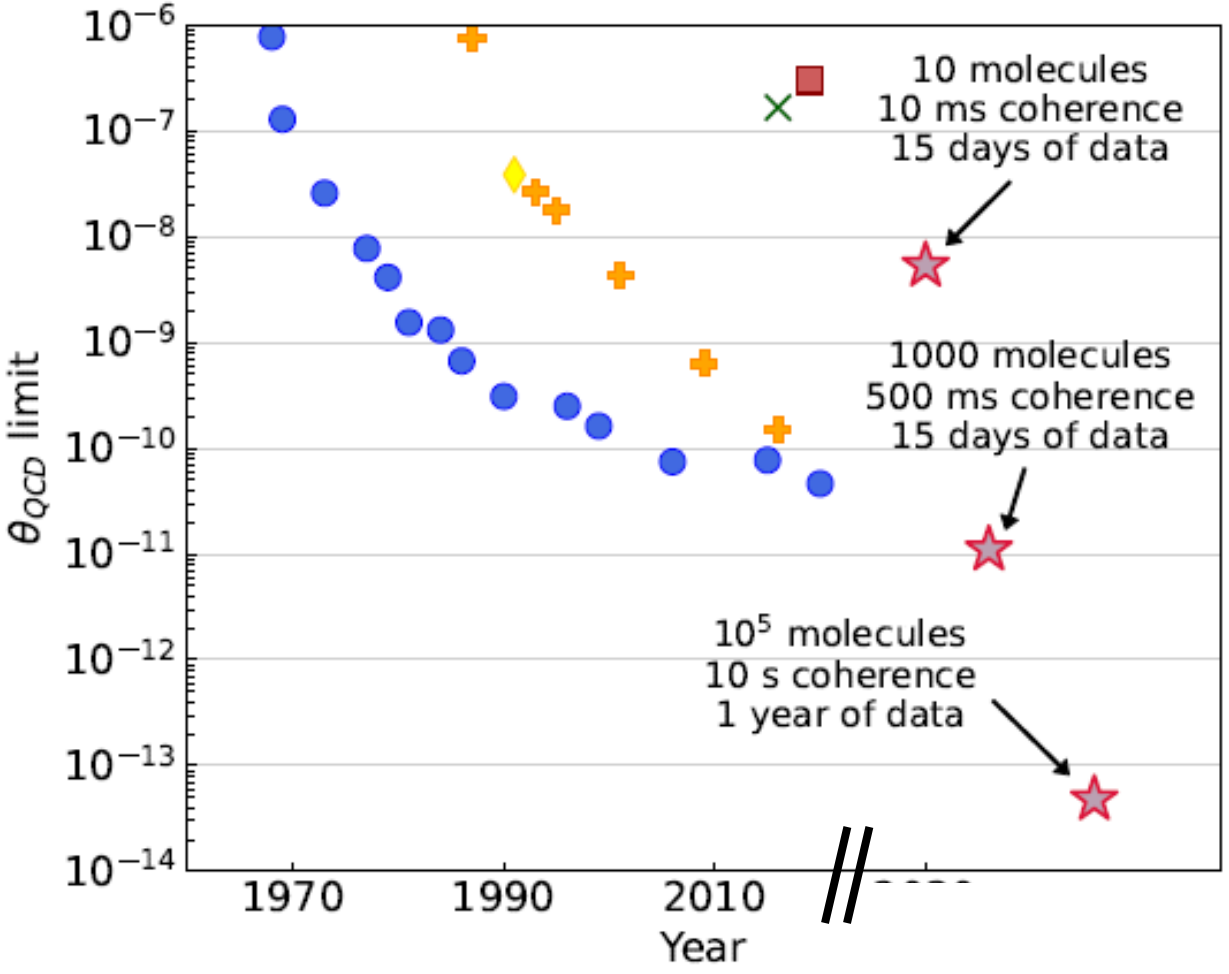
Radioactive molecules => Best of all worlds!

Hadronic EDM Limits

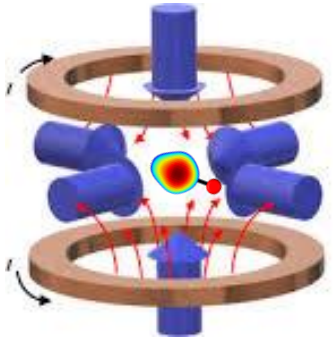
Weak Force

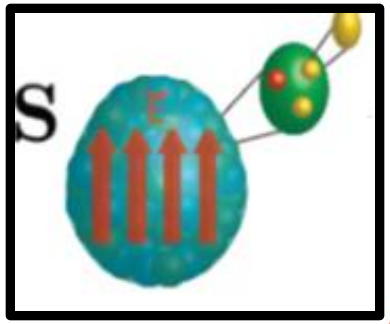


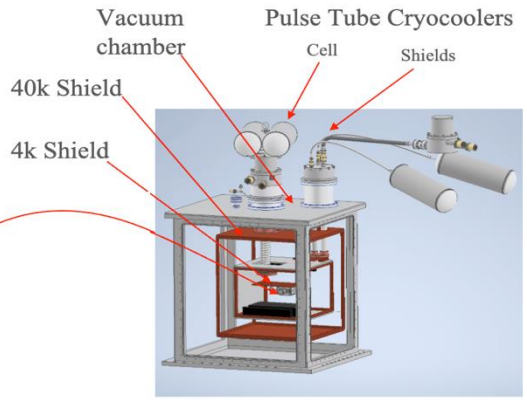
Strong Force

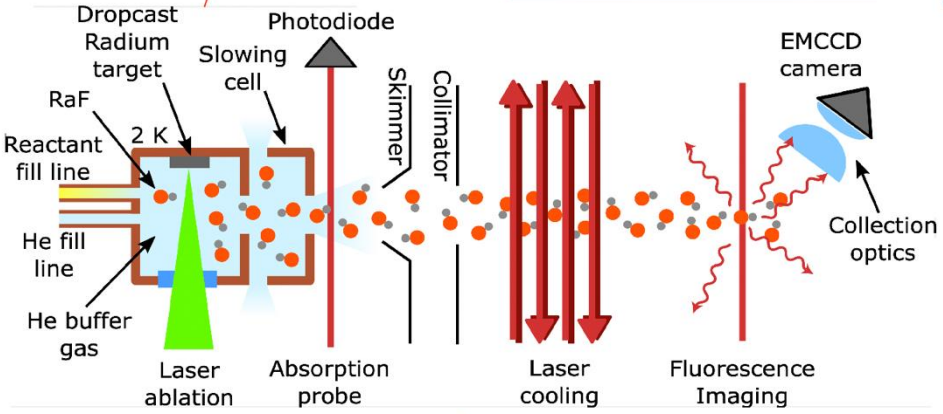


P,T-violation measurements with RaX Molecules









RaX Collaboration

J. Doyle (Harvard), N. Hutzler (Caltech), R.F. Garcia Ruiz (MIT) & FRIB

FRIB

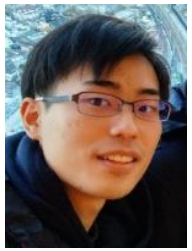
Caltech


S. Ebadi

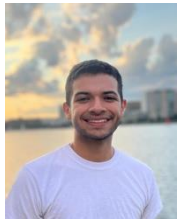

A. Jadbabaie


J. Munoz


M. Fulghieri

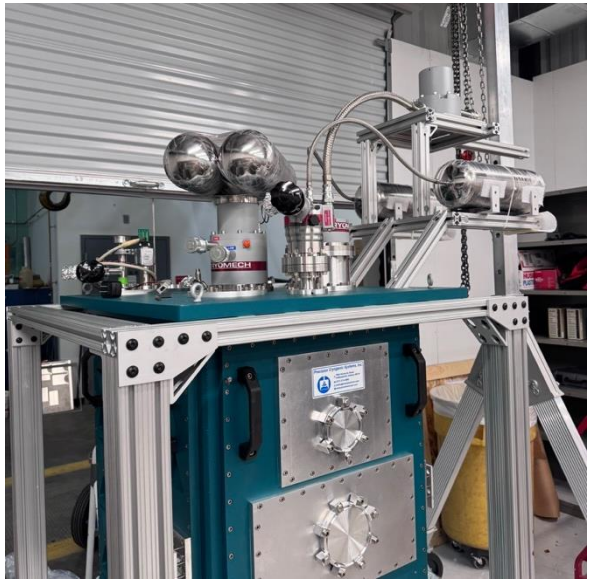

F. Shungo


K. Khusainova

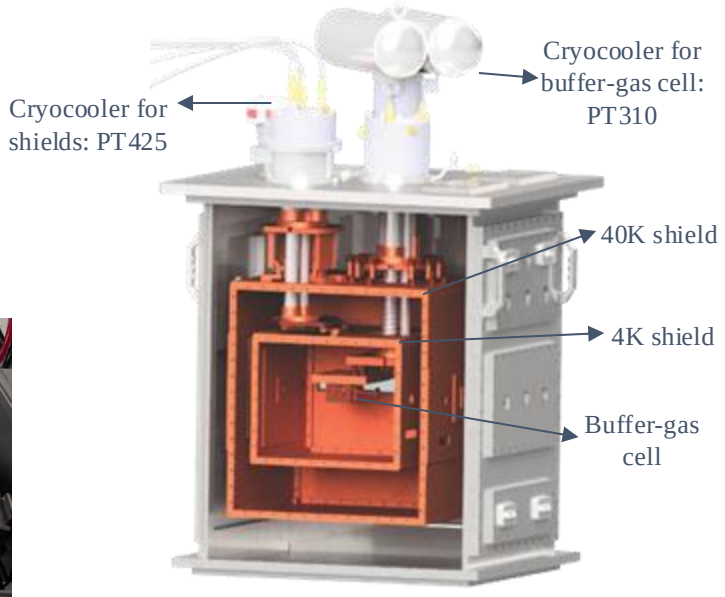

S. Munoz

RaX Collaboration

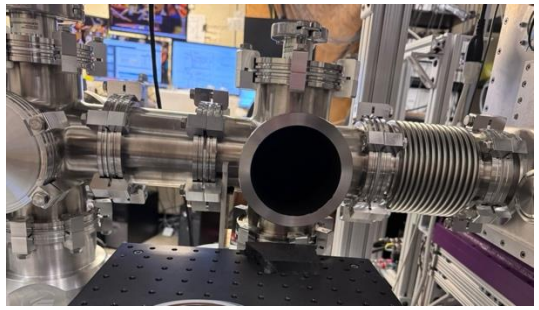
- ✓ Beam box fabrication
- ✓ Cryocooler testing
- ✓ Laser Installation
- ✓ Beamline construction



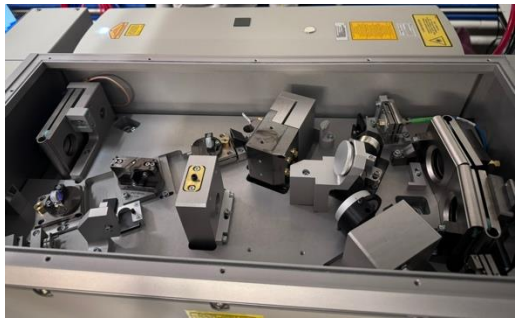
RaX @ Harvard



PT310 cryocooler:
2.2K base temp,
1W@3K, 51W@34K



Blackened beamline for fluorescence collection

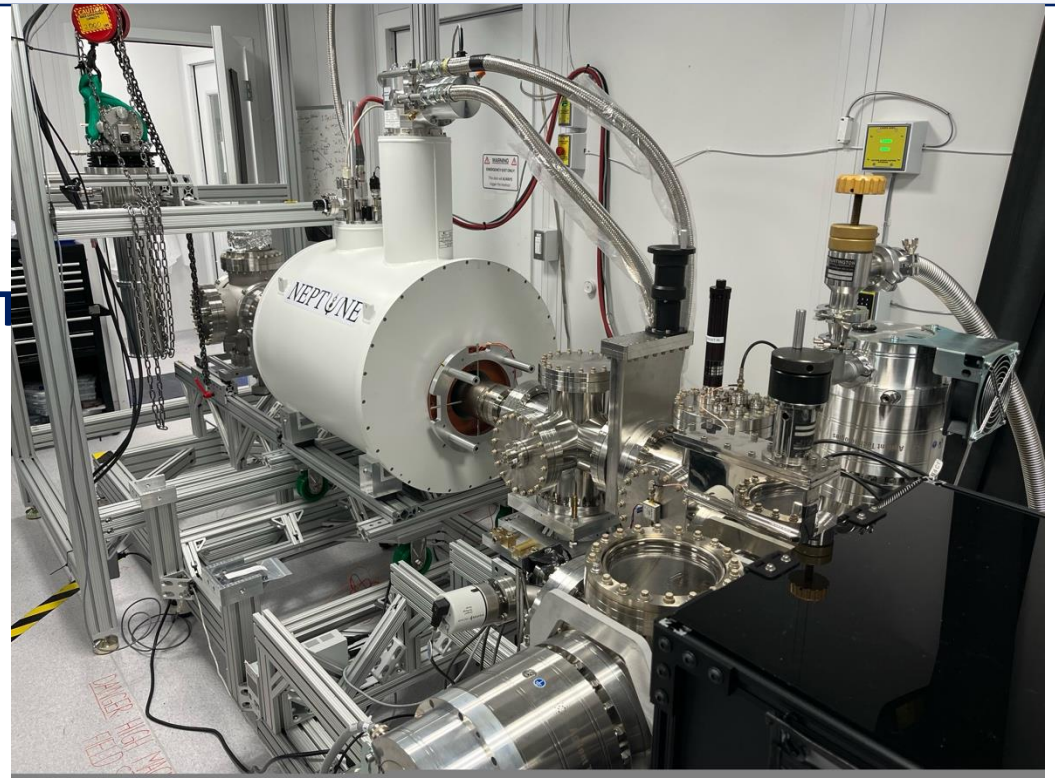


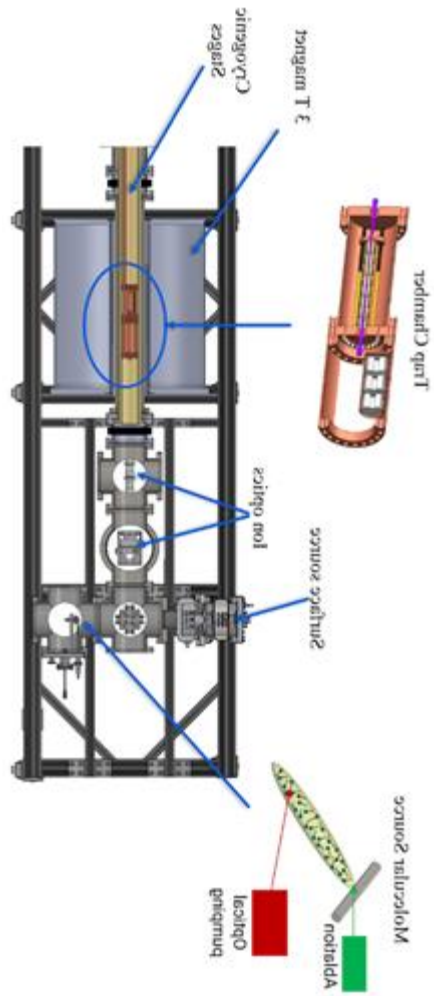
Ti:Sa laser installed

NEPTUNE – Project

Nuclear Electroweak Measurements in a Penning Trap Using Near-degenerate Energy States of Molecules

Lab @MIT





PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About

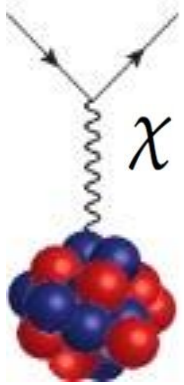
Electroweak Nuclear Properties from Single Molecular Ions in a Penning Trap

J. Karthein, S. M. Udrescu, S. B. Moroch, I. Belosevic, K. Blaum, A. Borschevsky, Y. Chamorro, D. DeMille, J. Dilling, R. F. Garcia Ruiz, N. R. Hutzler, L. F. Pašteka, and R. Ringle
Phys. Rev. Lett. **133**, 033003 – Published 19 July 2024

SCORPIONS

Atom/molecule
Nuclear

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} + \alpha_{\rm NP}X_i\gamma_{AA'}$$

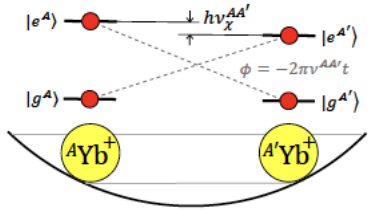


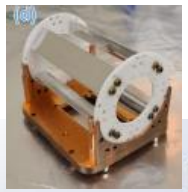
Yb → Vuletic's group at MIT

Accuracy ~ 300 Hz (stable) Vs ~ 1 MHz (exotic)

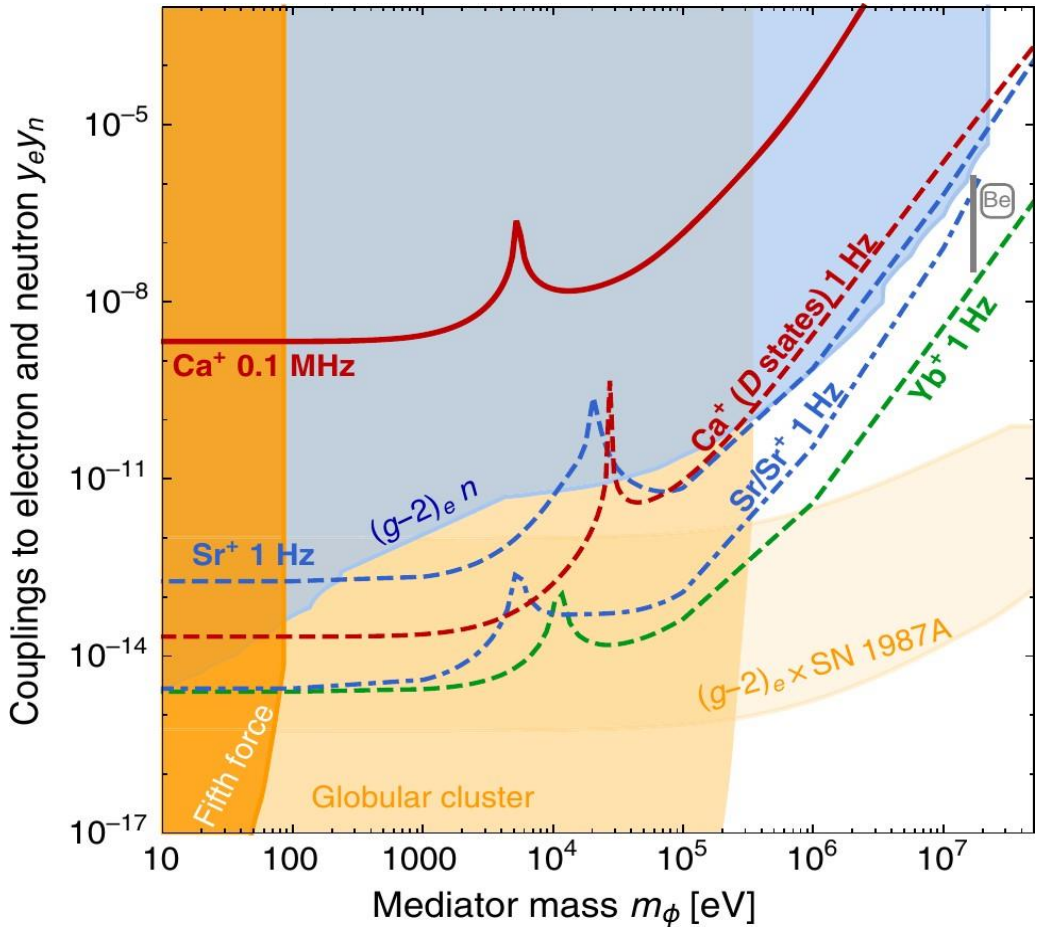
[Counts et al. Phys. Rev. Lett. 125, 123002 (2020)]

[J. Hur et al. Phys. Rev. Lett. 128, 163201 (2022)]



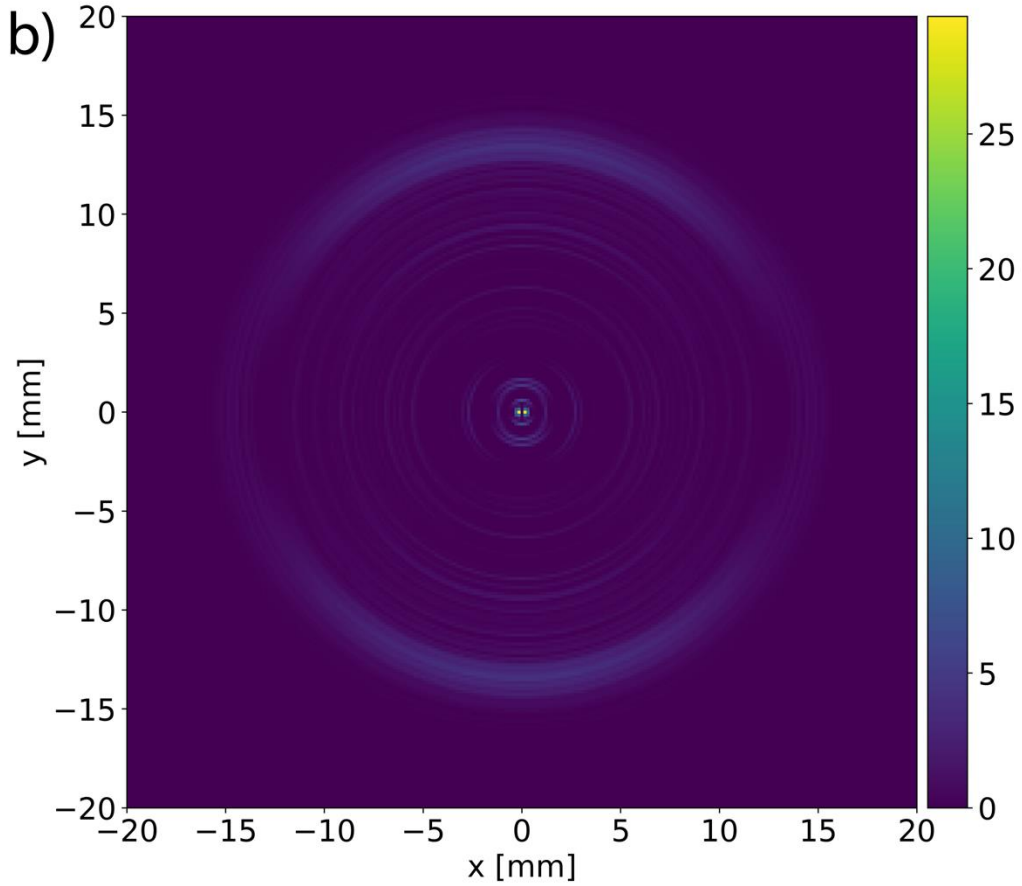


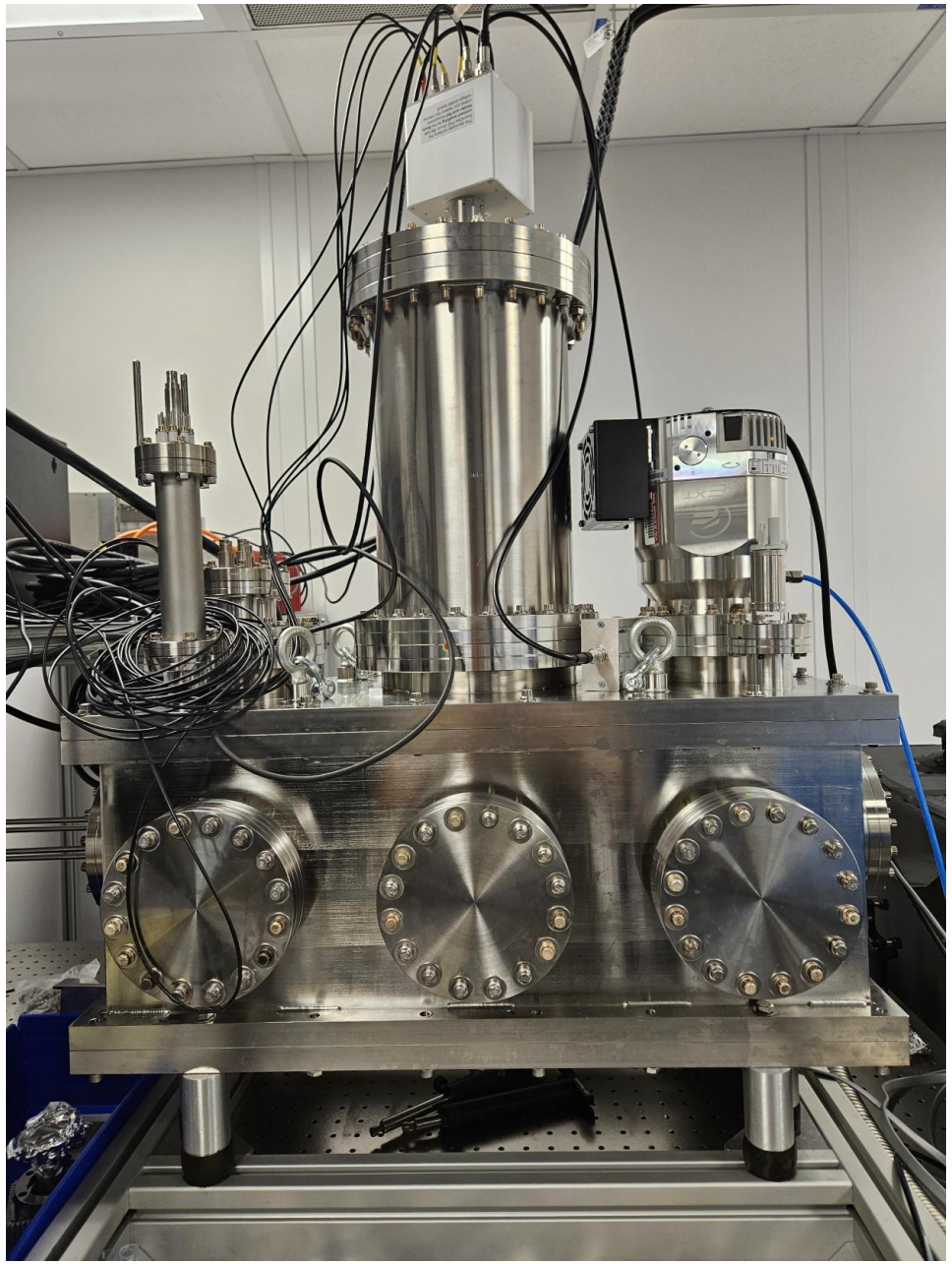
MIT student: Alex Brinson



[Berengutet al. Phys. Rev. Lett 120, 091801 (2018)]

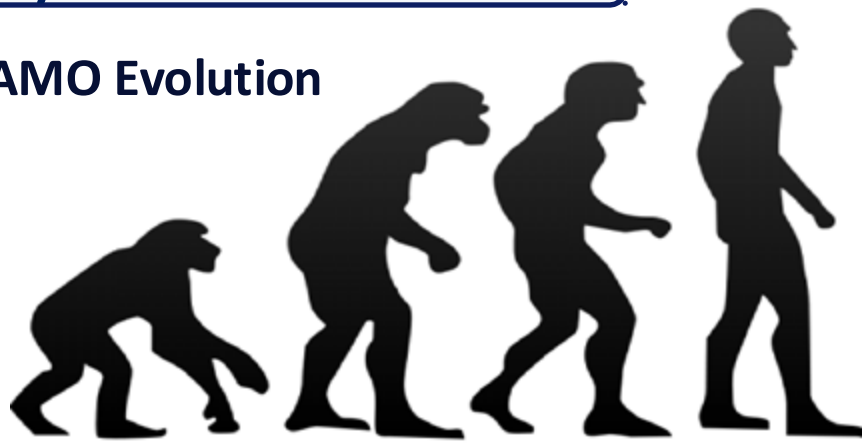
PRECIOSA – First Results



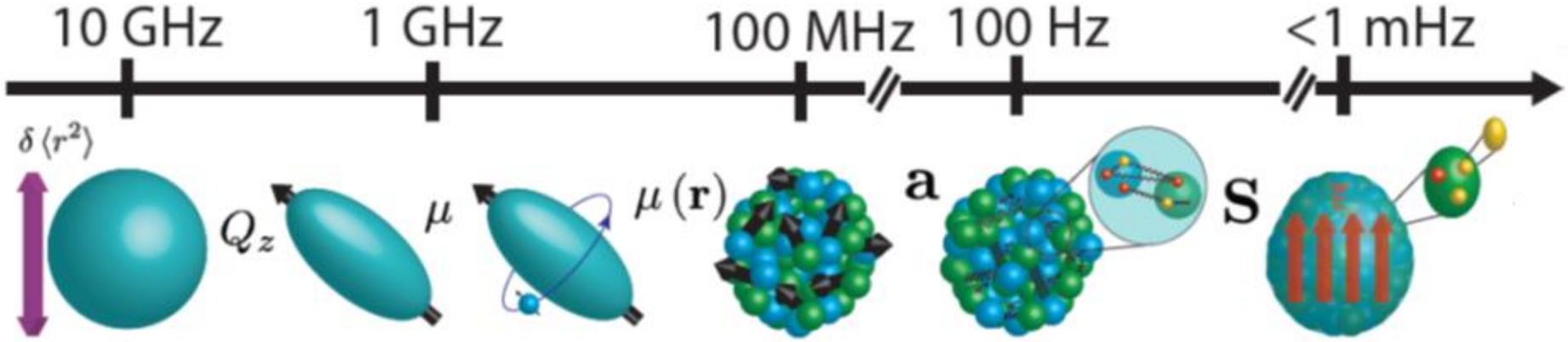


- Yb transition @ 262 nm - $^1S_0(4f^{14}6s^2) \rightarrow^3 P_1(4f^{14}6s7p)$
- Fully tested VMI setup
- < 100 meV resolution
- < 1/min background events

Summary and Outlook



We are here!



$$H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-6}	10^{-8}	$<10^{-12}$	$<10^{-15}$